Hydraulic and Physical Properties of Stony Soils in a Small Watershed

Thomas J. Sauer* and Sally D. Logsdon

ABSTRACT

The presence of rock fragments in soil layers can have a profound impact on measured hydraulic properties. Variation of surface soil hydraulic properties influences the amount, distribution, and routing of overland flow. The objective of this study was to assess the effect of rock fragments and soil texture on infiltration, hydraulic conductivity, and related physical properties in soils of a small watershed in northwestern Arkansas. Single-ring and tension infiltrometer measurements at three pressure heads ($h = -0.03$, -0.06, and -0.12 m) were completed on the surface soil layer at 42 sites along three transects crossing the watershed. Upland (Nixa, loamy-skeletal, siliceous, active, mesic Glossic Fragiudults) and side slope (Clarksville, loamy-skeletal, siliceous, semiactive, mesic Typic Paleudults) soils had significantly less rock fragments, lower infiltration rates (i), and lower hydraulic conductivities (K) at and near saturation compared with the valley bottom soil (Razort, fine-loamy, mixed, active, mesic Mollic Hapludalfs). Average infiltration rate at $h = -0.03$ m for all soils was only 9% of the ponded value suggesting that pores >1 mm in diameter dominated water flow under saturated conditions. At saturation, hydraulic properties tended to increase with rock fragment content while, at $h = -0.12$, the opposite was true. It is hypothesized that the source of rock fragments (weathering in place vs. colluvial and alluvial origin) and contact with the surrounding fine-earth fraction influence water flow by affecting hydraulic continuity near fragment surfaces. These relatively subtle morphological factors may have a disproportionate impact on water flow under near-saturation conditions in these soils.

Spatial variation of surface soil hydraulic properties influences the amount and distribution of infiltration and the routing of overland flow. Nonuniform infiltration leads to differences in the amount of plant-available water stored in the root zone, evaporation from the soil, and plant transpiration (Luxmoore and Sharma, 1980; Kachanoski and De Jong, 1988; Nielsen et al., 1996; Grayson et al., 1997). Water moving through the root zone or across the soil surface transports agricultural chemicals that can become pollutants when delivered to ground or surface waters. Understanding the spatial variation of soil hydraulic properties is critical to developing and implementing management practices that optimize plant water use and minimize nonpoint source impacts from agricultural practices (Or and Hanks, 1992; Gburek and Sharpley, 1998; Walter et al., 2000).

Recent expansion of the poultry industry in the Ozark Highlands (36–38° N lat., 91–95° W long.) has resulted in a marked intensification of agricultural land use. The availability of poultry litter (manure with bedding material) as a nutrient source for pasture lands has led to increased forage production and stocking rates of grazing livestock. Concentrated animal agriculture and land application of animal manures have increased concerns regarding nutrient loads in runoff and accelerated eutrophication of regional water bodies (Wagner and Woodruff, 1997). Better understanding of surface hydrology in the region is needed to develop best management practices for animal manure management that incorporate information on the spatial distribution of water flow patterns.

Many soils in the Ozark Highlands were formed from limestone, sandstone, or shale residuum and often contain high amounts of rock fragments. Rock fragments are defined as coarse fragments >0.002 m in diameter (Miller and Guthrie, 1984). Rock fragments in soils of the Ozark Highlands represent weathering-resistant inclusions within the original bedrock (e.g., chert) or parent material remnants. With natural and culturally accelerated erosion, rock fragments from higher elevations have accumulated at the base of slopes (colluvium) and in floodplains and drainage ways (alluvium). The amount and type of rock fragments in surface soil layers can affect infiltration and water storage, which in turn influence land use and site productivity (Ravina and Magier, 1984; Brakensiek and Rawls, 1994; Poesen and Lavee, 1994). Rock fragments influence soil hydraulic properties by affecting soil porosity and the tortuosity of water flow paths. With increasing amounts of nonpermeable rock fragments, the area available for water flow decreases, tortuosity of the flow paths increase, and overall water movement can become restricted (Mehuys et al., 1975).

Variation of rock fragment content in surface soils could have significant effects on the spatial distribution of runoff and consequences for agrichemical movement in the environment. The objective of this study was to assess the effect of rock fragments and soil texture on infiltration, hydraulic conductivity, and related physical properties in soils of a small watershed in northwestern Arkansas. Hydraulic properties of the surface soil layer are interpreted with respect to soil type, land use, and position in the watershed. Infiltration and hydraulic conductivity data from this study are compared with previous measurements made adjacent to and within the same watershed using other techniques as reported by Sauer et al. (1998, 2000).

MATERIALS AND METHODS

Field Site

All field measurements were completed in a 147-ha watershed, referred to as Basin 1, located near the town of Savoy, Arkansas (36° 7′ N lat., 94° 21′ W long.). The local topography

T.J. Sauer, USDA-ARS, Poultry Production and Product Safety Research Unit, Univ. of Arkansas, Fayetteville, AR 72701; currently at USDA-ARS, National Soil Tilth Lab., 2150 Pammel Drive, Ames, IA 50011-4420; S.D. Logsdon, USDA-ARS, National Soil Tilth Lab., 2150 Pammel Drive, Ames, IA 50011-4420. Received 14 Nov. 2001. *Corresponding author (sauer@nstl.gov).

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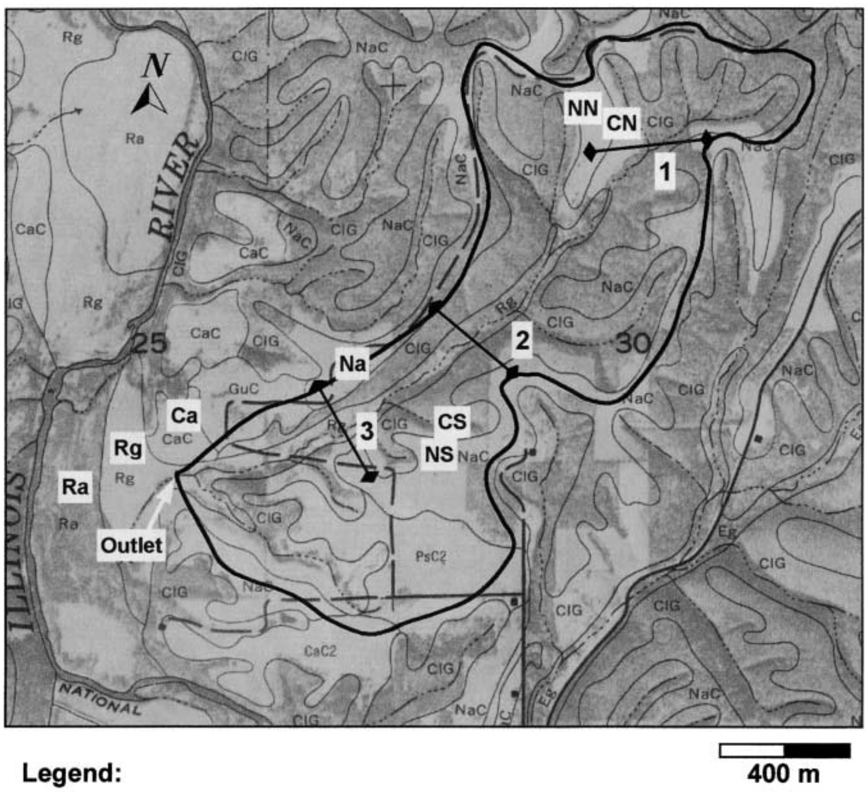
Abbreviations: MSL, mean sea level.

is ridge and valley with elevation in the watershed ranging from 317 m at the outlet to 376 m on the eastern boundary. Basin 1 is drained by an ephemeral channel that runs from northeast to southwest and discharges into the Illinois River. Average annual precipitation for the area is 1119 mm with mean January and July air temperatures of 1.1 and 25.9°C, respectively (Owenby and Ezell, 1992). Because of excessive erosion and persistent late-summer drought conditions, most cropland in the area was converted to permanent pasture in the 1930s for use as grazing land for beef cattle (*Bos taurus*). Land cover in the watershed currently consists of hardwood forest (57%) and pasture (43%) with tall fescue (*Festuca arundinacea* Schreb.) the dominant forage.

Six soils are present in Basin 1 and the immediate area (Fig. 1). Two soils, the Clarksville cherty silt loam and Nixa cherty silt loam, dominate Basin 1 comprising 49 and 30%, respectively, of the watershed area. Both of these soils formed from cherty limestone residuum and include the family particle-size class skeletal in their taxonomic name. The skeletal classification is a visual field determination to indicate that rock fragments occupy >35% of the soil volume. Rock fragments in the Clarksville and Nixa soils are composed almost entirely of chert. Because of its steep slopes (12–60%) and high rock fragment content, most of the Clarksville soil was never under tillage and remains in its original land cover (hardwood forest). Currently, approximately 87% of the soil mapped as Clarksville in Basin 1 is forested. The Nixa soil is on flatter ridge tops so more areas of this soil were cleared for cultivation. Most of these fields have subsequently been converted to pasture, approximately 58% of the Nixa soil in Basin 1 is now pasture land.

The Razort silt loam and Razort gravelly silt loam soils formed in alluvial deposits of the Illinois River or any of several ephemeral tributary channels including Basin 1. The Pickwick silt loam (fine-silty, mixed, semiactive, thermic Typic Paleudults) and Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiudults) also formed in alluvium but on the stream terrace. The soil map of Basin 1 includes eroded phases of both the Pickwick and Captina soils. The Guin cherty silt loam, which is now called Waben cherty silt loam (loamy-skeletal, siliceous, active, mesic Ultic Hapludalfs), formed in cherty colluvium. There are small areas of Razort gravelly silt loam (9.6% of area) and Pickwick silt loam (8.3%) in Basin 1 with <2% of the watershed area mapped as Captina or



Legend:
CaC = Captina silt loam, 3-6%
CaC2 = Captina silt loam, 3-6%, eroded
ClG = Clarksville cherty silt loam, 12-60%
GuC† = Guin cherty silt loam, 3-8%
NaC = Nixa cherty silt loam, 3-8%
PsC2 = Pickwick silt loam, 3-8%, eroded
Ra = Razort silt loam, occasionally flooded
Rg = Razort gravelly silt loam, occasionally flooded

† The Guin series has been replaced by the Waben cherty silt loam.

Fig. 1. Soil map of the Savoy field site including a legend for the map unit labels (Harper et al., 1969). Transects 1, 2, and 3 refer to the measurement transects of this study. Labels Ra, Rg, Ca, and Na refer to double-ring infiltrometer sites reported in Sauer et al. (1998). Labels NN, CN, NS, and CS refer to sprinkling infiltrometer sites reported in Sauer et al. (2000).

Waben. Additional details regarding local geology and soil descriptions are given in Harper et al. (1969) and Sauer et al. (1998).

Hydraulic Property Measurements

In August of 1998, three transects were established from ridge top to ridge top across the main drainage channel of Basin 1 (Fig. 1 and 2). Three measurement sites were identified within each soil map unit on each side of the main drainage channel except Transect 1 where three measurement sites were located on each side of the channel within the Clarksville soil map unit. Sites were selected to be physically representative of the map units along the transect and were thus unevenly spaced. A total of 42 sites were selected, 12 on Transect 1 (Nixa and Clarksville soils) and 15 each on Transects 2 and 3 (Nixa, Clarksville, and Razort soils). A global positioning system was used to obtain coordinates and elevations for the measurement sites. Prior to infiltration measurements at pasture sites, the grass was clipped close to the soil surface and removed. At forested sites, the soil was cleared of leaf litter, branches, and twigs. The soil was then carefully leveled with minimal disturbance to facilitate infiltration measurements while maintaining the native pore structure. A sample of the surface (0–0.025 m) soil adjacent to each measurement site was collected to determine antecedent soil water content. Samples for water content determinations were oven dried for 24 h at 105°C to determine the gravimetric water content. A 0.075-m diam. aluminum ring was pressed approximately 0.02 m into the soil to measure ponded infiltration rate (i_s) under 0.01 m of head. Infiltration was manually recorded until steady-state conditions were established.

Tension infiltrometers were used to measure unsaturated infiltration rate (i_u) at pressure heads (h) of −0.03, −0.06, and −0.12 m (referred to as $i_{0.03}$, $i_{0.06}$, and $i_{0.12}$, respectively). Infiltrometers used in this study were of the same design as described by Ankeny et al. (1988) without pressure transducers for automated recording. The base of the infiltrometer was 0.076 m in diameter. The infiltration ring was carefully removed just as the last of the water entered the soil. A thin (5 mm) layer of moist contact sand was then applied to the surface to cover exposed rock edges. The contact sand contained 0.8, 52.5, 42.7, and 4.0% very coarse, coarse, medium, and fine sand, respectively. A tension infiltrometer adjusted to −0.03 m of pressure head was immediately placed on the contact sand and readings of water influx manually recorded at 2 to 5 min intervals until steady state conditions were reached (generally ~1 h). Unsaturated infiltration measurements were completed sequentially at −0.03-, −0.06-, and −0.12-m pressure heads by selecting different air entry tubes on the infiltrometers bubble tower.

The use of a contact sand was necessary to provide a level measurement surface and to prevent damage to the nylon fabric membrane on the base of the tension infiltrometer. Perroux and White (1988) and Reynolds and Zebchuk (1996) discuss concerns regarding the use of contact material with tension infiltrometer measurements. To avoid measurement errors, Perroux and White (1988) recommended that the layer of contact material be as thin as possible, have a hydraulic conductivity (K) greater than or equal to the K for the soil, and have a water-entry potential (ψ_w) less than the minimum pressure head used. The contact material used in this study had a saturated hydraulic conductivity (K_s) of 8.98×10^{-4} m s^{-1} and a ψ_w of −0.11 m, indicating that this sand was an acceptable contact material for the soils studied. Tension infiltrometer measurements can be made using either ascending or descending pressure heads. Generally, tension infiltrometer measurements with descending heads are discouraged because of hysteresis effects induced by both wetting and drying within the flow field beneath the nylon membrane (Reynolds and Elrick, 1991; White et al., 1992; Jarvis and Messing, 1995). In this study, however, measurements with descending heads were used to avoid nonwetting behavior (hydrophobicity) of the soils observed during preliminary measurements.

All infiltration measurements were completed between 7 and 17 Aug. 1998. At one location on Transect 2 and three locations on Transect 3 (all Nixa sites), values of i_s were less than i_u for all pressure heads. These i_s values were discarded and not used in any subsequent analysis. At one location (Clarksville soil on Transect 1), a leak developed on the tension infiltrometer membrane that prevented completion of the $i_{0.12}$ measurement. Hydraulic conductivities (K_s and K_u's at h = −0.03, −0.06, and −0.12 m) at each pressure head (referred to as $K_{0.03}$, $K_{0.06}$, and $K_{0.12}$, respectively) were determined from measured infiltration rates using the nonlinear regression method of Logsdon and Jaynes (1993). The Logsdon and Jaynes (1993) procedure uses a single exponential $K(h)$ relationship for the three h levels, and a separate $K(h)$ relationship between the least negative h and ponded conditions.

Inverted infiltration rates (higher i at more negative h) or very small differences between i_s and $i_{0.03}$ prevented accurate determination of K_s at 12 sites (six Nixa, three Clarksville, and three Razort). Data sets are complete for $K_{0.03}$ and $K_{0.06}$ but three values are missing for $K_{0.12}$ (inverted i values at one Nixa site, no measurement at one Clarksville site, measured i = 0 at one Razort site).

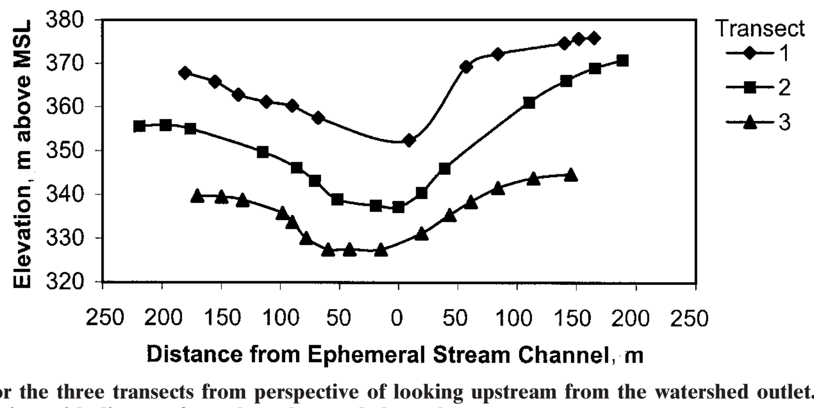


Fig. 2. Elevation profiles for the three transects from perspective of looking upstream from the watershed outlet. Points indicate locations of individual measurement sites with distance from the ephemeral channel.

Table 1. Physical properties of soils at the infiltration measurement sites by transect, soil, land use, and slope aspect†.

Data group	# of sites	Cobble	Coarse gravel	Fine gravel	Total rock fragments	Sand	Silt	Clay	Bulk density	<2-mm bulk density‡	<2-mm porosity
		%							Mg m^{-3}		%
Transect											
1	12	1.1§	34.9a	15.0	51.0	11.2	33.0	4.8b	1.40ab	0.92b	65.2ab
2	15	0.0	35.2a	18.3	53.5	11.3	30.9	4.3b	1.36b	0.85a	67.8a
3	15	2.3	19.4b	19.2	40.9	12.4	40.0	6.7a	1.46a	1.08a	59.4b
Soil											
Nixa	18	0.0	28.3	14.7b	43.0b	11.3	39.5a	6.2a	1.42	1.02a	61.4b
Clarksville	18	2.7	26.5	17.7b	46.8b	12.4	35.8a	5.0ab	1.41	0.98a	63.2b
Razort	6	0.0	42.0	26.5a	68.5a	10.6	17.3b	3.6b	1.37	0.65b	75.4a
Land use											
Forest	21	2.3	33.0	19.1	54.4a	11.3	29.6b	4.8	1.37b	0.83b	68.5a
Pasture	21	0.0	26.0	16.2	42.2b	12.1	39.8a	5.8	1.44a	1.06a	60.1b
Slope aspect											
South/East	18	2.7	28.4	14.1b	45.2b	12.0	36.7a	6.0	1.38	0.96a	64.0b
North/West	18	0.0	26.4	18.3b	44.7b	11.7	38.5a	5.0	1.44	1.04a	60.6b
Neutral	6	0.0	42.0	26.5a	68.5a	10.6	17.3b	3.6	1.37	0.65b	75.4a

† All soil separates are on a percentage by weight basis.
‡ Assumes all rock fragments have a density of 2.65 Mg m^{-3}.
§ Mean values of physical properties in a column for each data group followed by the same letter are not significantly different at $P = 0.05$ as determined by Fisher's protected least significant difference test. The absence of letters indicates no significant differences for that property.

Physical Property Measurements and Data Analysis

After the $h = -0.12$ m tension infiltration measurement was completed, the infiltrometer was removed, contact sand scraped away, and a surface sample collected from the soil directly under the infiltrometer to measure final water content. The excavation method was used to determine soil bulk density (Blake and Hartge, 1986). An excavation approximately 0.15 m in diameter and 0.05 m deep was made directly under each measurement site. The soil removed was oven dried at 105°C for 24 h to determine the oven-dry soil weight. The volume of the extracted soil was determined by lining the excavation with thin plastic and then recording the volume of water necessary to fill the cavity. Bulk density of the fine-earth fraction (<0.002-m diam.) was determined by subtracting the contribution of the cobble and gravel assuming a particle density of 2.65 Mg m^{-3} for the chert fragments.

Particle-size and water-retention analyses were performed on the soil removed during the bulk density determination. Samples were sieved to remove cobble-sized particles (>0.076-m diam.), ground with a mortar and pestle, then sieved to remove coarse and fine gravel-sized particles (>0.0127 and >0.002-m diam., respectively). A subsample of the soil remaining was used to determine sand, silt, and clay content using the hydrometer method (Gee and Bauder, 1986). The sand was further separated into the five size fractions of the USDA classification system by dry sieving. Water retention was measured on the fine-earth fraction using a hanging water column apparatus (Bouma et al., 1974). A 0.075-m diam. aluminum ring 0.05-m tall was placed on the sintered glass plate and filled to 0.025 m with a subsample of the fine-earth fraction packed to its field bulk density. The sample was saturated overnight and then water content values on the primary drying and wetting curves were determined at $h = 0, -0.03, -0.06, -0.12, -0.25$, and -0.40 m.

Data from each measurement site were grouped and analyzed independently by transect (1, 2, and 3), by soil (Nixa, Clarksville, and Razort), by land use (forest and pasture), and by slope aspect (south/east, north/west, and neutral). Differences among measured parameters within each of these groupings were analyzed using one-way analysis of variance (ANOVA) and Fisher's protected least significant difference (LSD) (Steel and Torrie, 1980). All statistical analyses were completed at the $P = 0.05$ level of confidence. Logarithmic transformations of the raw data were completed on data sets having unequal variances. When transformations were used, means from the untransformed data are presented.

RESULTS

The four data groupings reveal distinct differences in the trends of soil physical and hydraulic properties (Tables 1 and 2). The fewest number of significant differences were observed when comparing the three transects. This suggests that each transect provided a relatively unbiased sample of Basin 1 soil properties. Transect 3 had significantly less coarse gravel, higher bulk densities, and lower porosity of the fine-earth fraction than Transects 1 and 2. However, no statistically significant differences in hydraulic properties were observed among transects.

When comparing properties by soil, no significant differences between the Nixa and Clarksville soils were observed for any parameter. However, parameters for both of these soils were often different from those of the Razort soil. The Nixa and Clarksville soils had significantly less gravel and total rock fragments, and significantly more silt. These textural differences were manifested as significantly greater bulk density and lower porosity of the fine-earth fraction in Nixa and Clarksville soils compared with the Razort soil. The Razort soil has significantly greater i_s, K_s, $i_{0.03}$, and $K_{0.03}$. There were no statistically significant differences for $i_{0.06}$ or $K_{0.06}$ among soils but the trends reversed at $h = -0.12$ m. This trend reversal is likely due to poor hydraulic continuity between rock fragments in the Razort soil at more negative pressure heads. For example, no infiltration was observed up to 1.5 h after adjusting the tension infiltrometer to $h = -0.12$ m at one sampling location (Razort soil, Transect 2), indicating the absence of any significant amount of continuous small pores. The soil at this site had the highest coarse fragment content (83.4%) of any sampling location. At $h = -0.12$ m, i_u for the Razort soil was significantly lower than for the Nixa and Clarksville. The Razort $K_{0.12}$ was also lower

Table 2. Ponded infiltration rate and saturated hydraulic conductivity by transect, soil, land use, and slope aspect.

Data group	# of sites	Infiltration rate: Ponded	$h = -0.03$ m	$h = -0.06$ m	$h = -0.12$ m	Hydraulic conductivity: Saturated	$h = -0.03$ m	$h = -0.06$ m	$h = -0.12$ m
		mm h^{-1}							
Transect									
1	12	238†	29.2	18.2	10.0	144	15.5	10.4	5.0
2	15	850	59.0	18.9	14.3	148	25.3	11.1	6.0
3	15	332	38.9	21.6	13.6	30.3	22.8	12.9	7.9
Soil									
Nixa	18	158b	33.5b	21.8	14.3a	80.2b	17.2b	12.8	7.7
Clarksville	18	139b	23.7b	17.9	13.3a	89.3b	11.5b	9.3	6.2
Razort	6	2340a	132a	18.4	6.2b	444a	65.2a	14.2	2.9
Land use									
Forest	21	746	54.7	17.6	11.3	125	26.6	10.4	5.4b
Pasture	21	148	31.9	21.6	14.5	113	16.6	12.7	8.3a
Slope aspect									
South/East	18	146b	24.9b	18.1	13.0a	84.7b	13.3b	10.5	6.8
North/West	18	149b	32.3b	21.5	14.4a	86.1b	15.4b	11.7	7.2
Neutral	6	2340a	132a	18.4	6.2b	444a	65.2a	14.2	2.9

† Mean values of hydraulic properties in a column for each data group followed by the same letter are not significantly different at $P = 0.05$ as determined by Fisher's protected least significant difference test. The absence of letters indicates no significant differences for that property.

than the Nixa and Clarksville soils but these differences were not significant at $P = 0.05$.

Differences in physical and hydraulic properties among soils influenced the analyses based on land use and slope aspect because of the distribution of soils. All of the Razort sites, 12 of the 18 Clarksville sites, and three of the Nixa sites were located in forested areas. Conversely, 15 of the 18 Nixa sites and only six of the Clarksville sites were located in pasture. As the Nixa and Clarksville soils were found to have similar properties, differences between forest and pasture sites can be attributed to the presence of all of the Razort measurement sites within forested areas. The forest sites had significantly more rock fragments, less silt, lower bulk densities, and higher porosity in the fine-earth fraction. Forest sites had higher i and K values at saturation, and $h = -0.03$ m while pasture sites had higher i_u and K_u values at $h = -0.06$ and -0.12 m. These differences were significant in only one case ($i_{0.12}$ at forest sites > pasture sites).

Analysis of transect data by slope aspect assesses the presence of asymmetry in physical or hydraulic properties across the main channel of Basin 1. In this instance, the south/east (left side when facing upstream) and north/west (right side when facing upstream) classifications include equal numbers of sites on Nixa and Clarksville soils (nine per soil). Mean elevations for the Nixa and Clarksville sites were 357.9 and 347.9 m above mean sea level (MSL), respectively. The neutral classification includes the sites on Razort soil in the valley bottom (mean elevation 332.7 m above MSL). The statistical analyses show remarkably little difference in measured properties between the south/east and north/west sites although both were significantly different than neutral sites for 10 of the 18 parameters. The neutral sites (Razort soil) had greater fine gravel and rock fragment content, lower silt content, and lower bulk density and higher porosity of the fine-earth fraction. The neutral sites also had significantly greater i_s, K_s, $i_{0.03}$, and $K_{0.03}$.

DISCUSSION

Ponded infiltration rates for the Nixa and Clarksville soils were approximately two to six times greater than previously measured in or near Basin 1 (Table 3, Fig. 1). Previous infiltration rate measurements were made with a double ring infiltrometer (0.30 m-diam inner ring, 0.05 m head) or a sprinkling infiltrometer (1 by 2 m plots, 75 mm h^{-1} for 1 h) (Sauer et al., 1998 and 2000). For the Razort gravelly silt loam, the ponded infiltration rate was 90 times greater than measured with a double ring infiltrometer on the nearby flood plain of the Illi-

Table 3. Comparison of ponded infiltration rate and saturated hydraulic conductivity for soils at the Savoy field site. Values are means ±1 standard deviation.

Hydraulic property/method	Soil: Captina silt loam	Clarksville cherty silt loam	Nixa cherty silt loam	Razort silt loam	Razort gravelly silt loam
	mm h^{-1}				
Ponded infiltration rate					
Double ring infiltrometer†	22.2 ± 18.3	–	20.4 ± 14.2	52.9 ± 55.5	26.0 ± 19.8
Sprinkling infiltrometer‡	–	54.4 ± 12.6	49.0 ± 15.4	–	–
Single ring infiltrometer (this study)	–	139 ± 113	126 ± 138	–	2340 ± 2520
Saturated hydraulic conductivity					
Constant head permeameter§	296 ± 233	–	312 ± 417	248 ± 191	1410 ± 615
Single ring infiltrometer (this study)	–	89.3 ± 77.0	80.2 ± 81.4	–	444 ± 468

† Measurement area = 0.073 m^2 (Sauer et al., 1998).
‡ Measurement area = 2 m^2 (Sauer et al., 2000).
§ Measured on undisturbed cores 0.075-m diam. by 0.10 m long (Sauer et al., 1998).

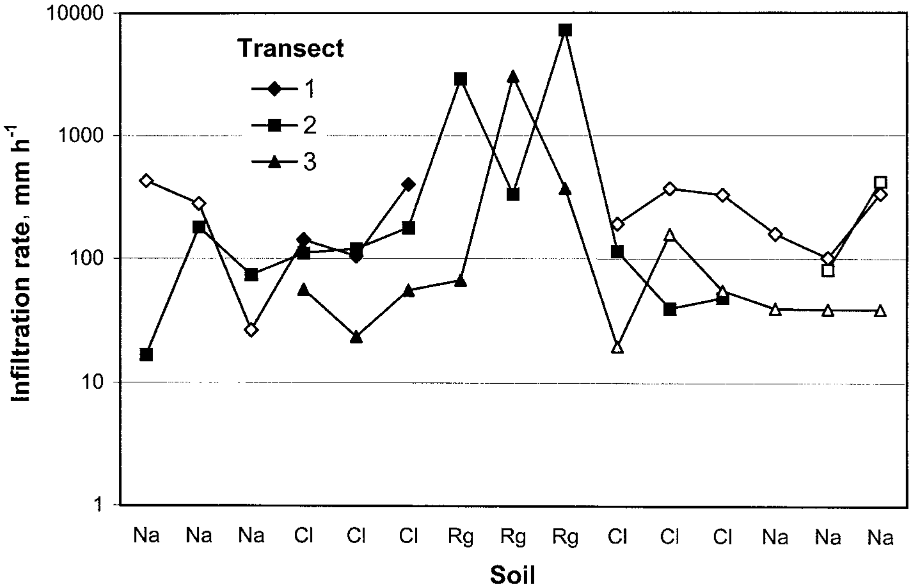


Fig. 3. Values of ponded infiltration rate, i_s, for each measurement location by soil for the three transects. The Nixa soil (Na) corresponds to the ridge tops, the Clarksville soil (Cl) to the side slopes, and the Razort soil (Rg) to the valley bottom. Hollow symbols indicate measurement locations in pasture, solid symbols indicate forest.

nois River (Sauer et al., 1998). The K_s values in this study were approximately three times less than those measured in the laboratory using undisturbed cores (0.076 m-diam. by 0.1 m long) collected at the double ring infiltrometer sites (Sauer et al., 1998). Differences among hydraulic properties measured in the different studies can be attributed to varying scales of the measurement areas, different measurement techniques, and spatial variation of soil properties in this heterogeneous terrain (Starr, 1990; Mallants et al., 1997; Reynolds et al., 2000). Seasonal effects are not likely as all measurements were made in summer.

When simultaneous measurements are available for both the Nixa and Clarksville soils, their hydraulic properties are significantly lower than for the Razort soil. Thus, in the Ozark landscape represented by Basin 1, all measurements consistently indicate that soils commonly found on the ridge tops and side slopes (Nixa and Clarksville) have lower infiltration rates, which can result in earlier and more runoff from these areas during storm events. The soil in the valley bottom of Basin 1 (Razort) has a significantly higher infiltration rate, which suggests that runoff water from upland areas can subsequently infiltrate in the valley bottom. Values of i_s at each measurement site in the current study graphically illustrate this spatial trend of infiltration rate (Fig. 3). The mean i_s for the Razort soil is more than an order of magnitude greater than for the Nixa and Clarksville soils. If the 14.1 ha of Razort soil had a mean i_s of 2.34 m h^{-1}, the amount of infiltration into this soil in 1 h would be equivalent of 0.248 m h^{-1} of runoff from the upland soils of Basin 1 (132.9 ha). Field observations are in conceptual agreement with this finding as, on several occasions, evidence of runoff from upland areas of Basin 1 were observed (i.e., debris trails on side slopes) while no runoff was detected at the watershed outlet. Discharge at the watershed outlet has only been observed when prior precipitation events have raised the shallow groundwater level in the valley bottom to near the soil surface. Saturated conditions near the soil surface thwart infiltration of upland runoff, which is instead routed across the soil surface to the ephemeral channel and out of the watershed.

Infiltration rates decreased precipitously with increasing negative pressure head (Fig. 4). On average for all measurement sites, $i_{0.03}$ was only 9.0% of i_s. Infiltration rate continued to decrease with increasingly negative h as $i_{0.06}$ and $i_{0.12}$ were 4.0 and 2.6%, respectively, of i_s. Capillary theory can be used to estimate the size of pores excluded from the transmission of infiltrating water at differing pressure heads. Assuming idealized cylindrical pores, pore radii conducting water at a particular pressure head (h) can be predicted from

$$r = -\frac{2\sigma\cos\alpha}{\rho g h} \quad [1]$$

where σ is the surface tension of water (N m^{-1}), α is the contact angle between water and the pore wall (assumed = 0°), ρ is the density of water (Mg m^{-3}), and g is the acceleration due to gravity (9.8 m s^{-2}). From Eq. [1], pressure heads of −0.03, −0.06, and −0.12 m would exclude pores greater than 1, 0.5, and 0.25 mm-diam. The dramatic reduction in i from saturated conditions to −0.03 m of pressure head indicates that large pores (>1 mm-diam.) dominated flow under saturated conditions. The relatively small differences among infiltration rates under unsaturated conditions indicate that pores in the 0.25- to 1-mm diam. range did not contribute significantly to saturated/ponded infiltration. The accuracy of the preceding discussion assumes that representing soil pores as cylindrical, vertical tubes is an adequate model for the macropores found in these soils. While such a model might be appropriate for soils in which

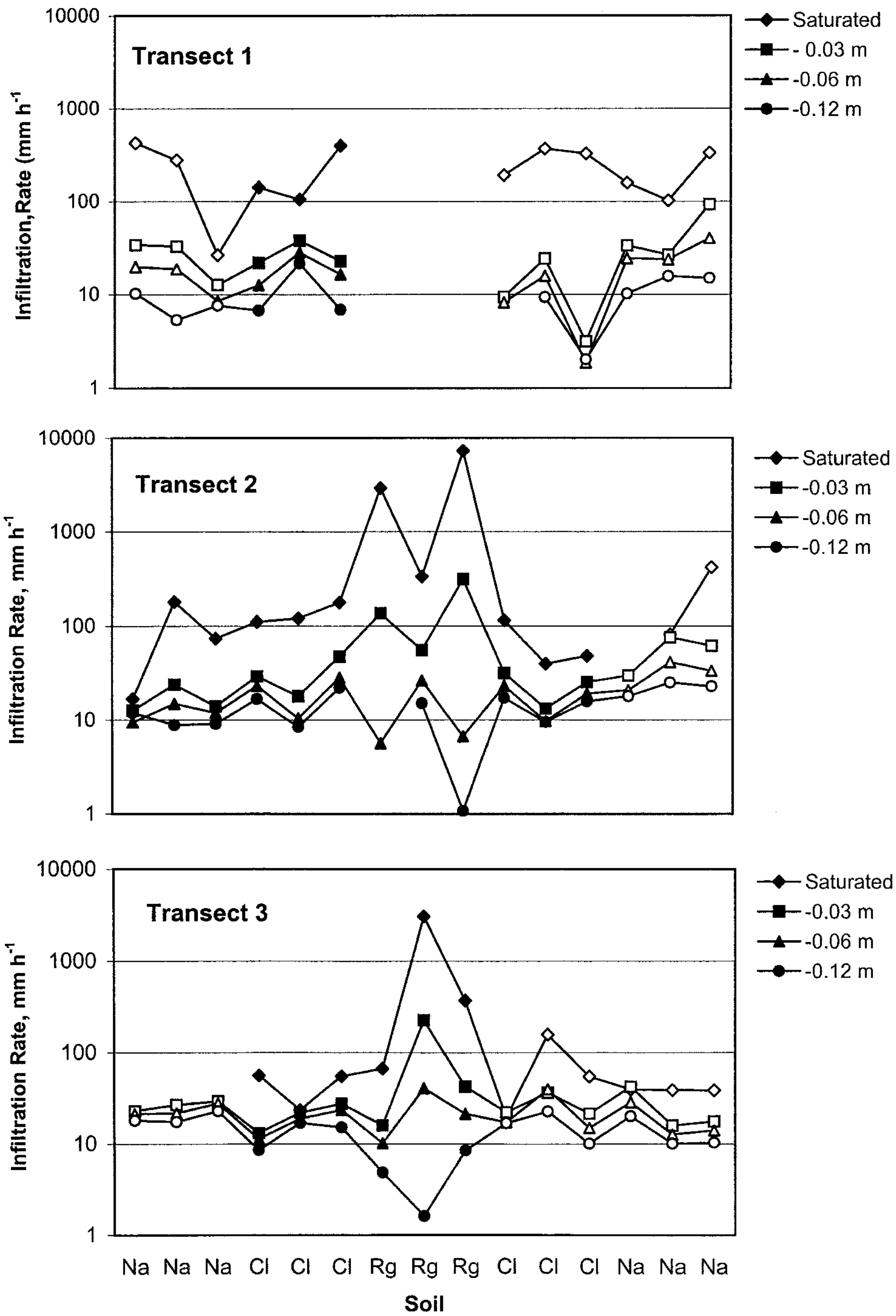


Fig. 4. Infiltration rates measured under ponded conditions and at three negative pressure heads at each location for the three measurement transects. The Nixa soil (Na) corresponds to the ridge tops, the Clarksville soil (Cl) to the side slopes, and the Razort soil (Rg) to the valley bottom. Hollow symbols indicate measurement locations in pasture, solid symbols indicate forest.

earthworm (e.g., *Lumbricus terrestris*) burrows or root channels are the dominant type of macropore, this may not be the case in the soils of Basin 1. Significant earthworm activity was not observed in these soils, possibly because of the high amount of coarse fragments and low soil pH (Curry, 1998; Sauer et al., 1998). It is instead likely that voids between the fine-earth fraction and the rock fragment surfaces are the dominant macropores in these soils.

Figure 5 presents mean K data for each soil against volumetric water content (θ) measured at the corresponding h for the fine-earth fraction as measured in the laboratory on the hanging water column apparatus. Trends in hydraulic conductivity with decreasing θ (i.e., increasing negative pressure head) are consistent with those for infiltration rate (Fig. 4). Note, however, that the θ values in Fig. 5 were determined from repacked soil samples that may not accurately represent the structure of the field soil. The sharp break in the $K(\theta)$ relationship at $h = -0.03$ m is similar to trends observed

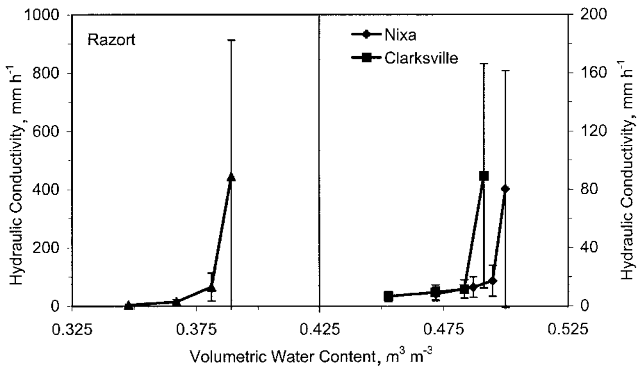


Fig. 5. Mean hydraulic conductivity by soil at varying volumetric water content corresponding to $h = 0, -0.03, -0.06$, and -0.12 m. Water contents were determined on the fine-earth fraction only using hanging water column apparatus.

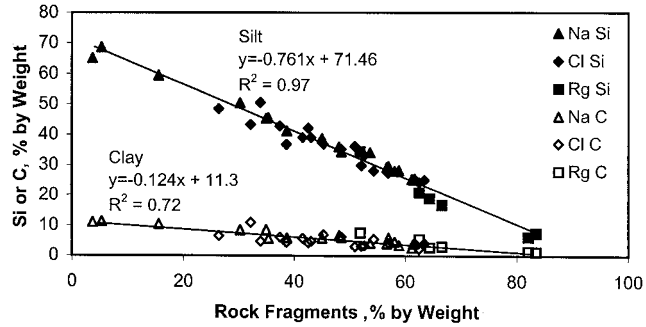


Fig. 6. Silt and clay content vs. rock fragment content for the Nixa (Na), Clarksville (Cl), and Razort (Rg) soils.

in other soils (Sauer et al., 1990; Ankeny et al., 1991; Clothier et al., 1995). Again, it is evident that large pores (> ~1-mm diam.) are dominating the saturated flow of water through the soil. Also apparent is the lack of significant differences in K between the Nixa and Clarksville soils while both contrast sharply with K's for the Razort soil. The Razort soil had a significantly lower bulk density and higher porosity of the fine-earth fraction, producing higher K values but lower θ at each h (Fig. 5). The values of θ for the Razort soil were significantly lower at all pressure heads compared with the Nixa and Clarksville soils.

Efforts to develop distinct relationships between any of the measured hydraulic properties and rock fragment content produced only poorly correlated relationships ($R^2 < 0.45$). In general, under saturated conditions, infiltration rate and hydraulic conductivity tended to increase with increasing rock fragment content while, with increasing negative pressure head and particularly at $h = -0.12$ m, the hydraulic properties tended to decrease with increasing rock fragment content. If the fragments were of a rock type that absorbs water, obvious complications arise because of the differences in water retention and hydraulic properties of soil and rock (Reinhart, 1961; Hanson and Blevins, 1979; Brakensiek and Rawls, 1994). However, in this instance the rock fragments are composed of chert, which absorbs very little water (0.2% by weight, Gras and Monnier, 1963). Therefore, it can be assumed that the primary effect of rock fragments is in reducing the area for water transmission and increasing the tortuosity of the water flow paths (Mehuys et al., 1975; Childs and Flint, 1990).

Peck and Watson (1979) derived an equation for the ratio of field saturated hydraulic conductivity for a soil containing rock fragments to the hydraulic conductivity of the fine-earth fraction alone (K_{fe})

$$\frac{K_s}{K_{fe}} = \frac{2\,(1 - V_r)}{(2 + V_r)} \qquad [2]$$

where V_r is the fraction of the soil volume composed of rock fragments. Similarly, Bouwer and Rice (1984) used data from laboratory studies with sand-gravel mixtures to develop an expression using void ratios

$$\frac{K_s}{K_{fe}} = \frac{e_s}{e_{fe}} \qquad [3]$$

where e_s and e_{fe} are the void ratios for the bulk soil and fine-earth fractions, respectively. Equations [2] and [3] were used to estimate values of K_{fe} for each of the three soils. The Nixa and Clarksville soils had measured K_s's of 80.2 and 89.3 mm h^{-1} (Table 2), estimated K_{fe}'s of 127 and 145 mm h^{-1} from Eq. [2], and estimated K_{fe}'s of 181 and 200 mm h^{-1} from Eq. [3]. Thus, the K_{fe} values from Eq. [2] and [3] are 1.6 and 2.2 times greater, respectively, than the corresponding K_s's for both soils. The Peck and Watson (1979) estimates of K_{fe} for the Razort soil were similar to those for the Nixa and Clarksville (1.75 times greater than K_s) but the Bouwer and Rice (1984) estimate was 3.4 times greater than the measured K_s (1520 vs. 444 mm h^{-1}). The effect of the tortuosity induced by the presence of the rock fragments is therefore estimated to increase the water flow through the fine-earth fraction of these stony soils by a factor of ~1.5 to 3 as compared with the bulk soil.

El Boushi and Davis (1969) found that water can be retained on nonporous rocks as a thin film of water on the rock surface, as droplets at contact points, or in depressions on the upper surfaces. For deposits composed entirely of rock fragments (i.e., talus or cobble-covered beds in ephemeral streams), El Boushi and Davis (1969) concluded that infiltrating water could wet less than 50% of the rock surfaces. Under unsaturated conditions, relatively small areas represented by contact points provide the only hydraulic continuity. In soils containing rock fragments, however, it would be expected that the fine-earth fraction would provide hydraulic connection between and around nonporous rocks.

The previous discussion and the lack of a strong relationship between rock fragment content and any of the measured hydraulic properties encourages the investigation of possible interactions between rock fragment content and soil texture. Soil samples from the measurement sites exhibited strong negative correlations between rock fragment content and percentage of clay and silt (Fig. 6). A much less distinct relationship was found between rock fragment content and percentage of sand ($R^2 = 0.39$). Silt and clay content both tended to decrease with elevation, that is, Nixa > Clarksville > Razort as, concurrently, rock fragment content increased. Relationships between clay or silt content and hydraulic

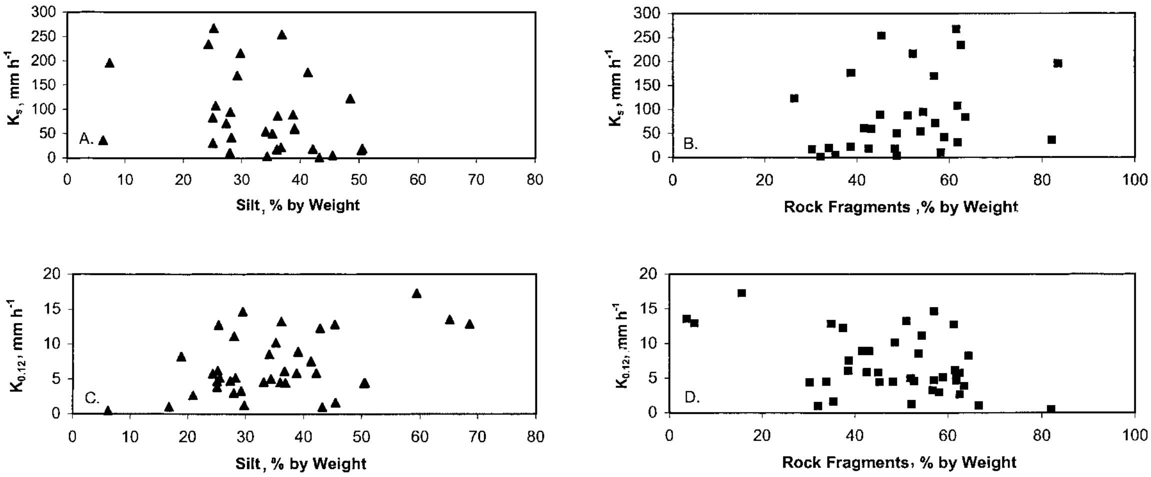


Fig. 7. Saturated hydraulic conductivity, K_s vs.(A) silt and (B) rock fragment content and hydraulic conductivity at $h = -0.12$ m, vs. (C) silt and (D) rock fragment content.

properties were not significantly better than for rock fragment content (Fig. 7). These results suggest that rock fragment, silt, or clay content on their own, did not significantly affect water flow in the surface soil layer of these soils.

An alternative interpretation of the hydraulic property data from this study is possible when considering the role of the fine-earth fraction in providing hydraulic continuity. In collecting the soil samples, it was observed that rock fragments in the Nixa soil often had clay coatings adhering to them and were tightly held in the soil matrix. Rock fragments from the Razort soil, however, did not have clay coatings and fit loosely within the soil matrix. This is explainable in that, for the upland soil, rock fragments are the product of weathering in place whereas, for the Razort soil, most of the rock fragments have been transported to their present location by gravity and water. Presumably, the soil coatings were removed in transport and the higher concentration of rock fragments in the Razort soil is the result of erosional deposition. The Clarksville soil is transitional in that rock fragments could be from both weathering and colluvial/alluvial origin. These observations are consistent with the data in Fig. 6, which show a marked depletion in clay and silt when moving down slope from the Nixa to Razort soils. It is proposed, therefore, that the weak trends found between rock fragment, silt, and clay content and soil hydraulic properties would be strengthened if it were possible to evaluate the effectiveness of the fine-earth fraction in providing hydraulic contact immediately adjacent to rock fragment surfaces. Innovative coupling of field techniques from soil morphology and soil physics may be necessary to further investigate this hypothesis in detail.

CONCLUSIONS

Analysis of trends between soil hydraulic properties and rock fragment content did not lead to distinct relationships. At saturation, hydraulic properties tended to increase with increasing rock fragment content while, at $h = -0.12$, the opposite was true, although both trends were weakly expressed. More generally, soils with similar rock fragment content were often found to have widely disparate infiltration rate and hydraulic conductivity values. Source of the fragments (weathering in place vs. colluvial and alluvial origin) and adhesion with the surrounding fine-earth fraction are suggested to influence water flow by affecting hydraulic continuity on fragment surfaces. It is proposed that these relatively subtle morphological factors can have a disproportionate impact on water flow in the soils of Basin 1 and are worthy of further study.

Understanding surface hydrologic processes is a key element in managing the soil water regime and reducing offsite movement of potential water quality contaminants. Results of this study indicate that there are distinct differences in soil hydraulic properties among three soils commonly found in association in the Ozark Highlands. Upland (Nixa) and side slope (Clarksville) soils have infiltration rates and hydraulic conductivities that are comparable but generally less than those for the soil found in the valley bottom (Razort). The Nixa soil, with its flatter slopes and lower rock fragment content, is preferred for permanent pasture land and therefore is likely to be managed more intensively than areas in forest. Increasing infiltration in areas of Nixa and Clarksville soils will reduce runoff from areas that routinely receive livestock manures or commercial fertilizers while protecting areas of the Razort soil will sustain its ability to capture runoff. Further research is necessary to assess whether the rapid transmission of water in the Razort soil facilitates the retention or transformation of nutrients contained in the captured runoff.

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